FERMILAB-PUB-08-231-E

Phenomenological interpretation of the multi-muon events reported by the CDF collaboration

P. Giromini,[1] F. Happacher,[1] M. J. Kim,[1] M. Kruse,[3] K. Pitts,[4] F. Ptohos,[2] and S. Torre[1]

[1] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[2] *University of Cyprus, Nicosia CY-1678, Cyprus*
[3] *Duke University, Durham, North Carolina 27708*
[4] *University of Illinois, Urbana, Illinois 61801*

Abstract

We present a phenomenological conjecture of new physics that is suggested by the topology and kinematic properties of the multi-muon events recently reported by the CDF collaboration. We show that the salient features of the data can be accounted for by postulating the pair production of three new states h_1, h_2, and h_3 with masses in the range of 15, 7.3, and 3.6 GeV/c^2, respectively. The heavier states cascade-decay into the lighter ones, whereas the lightest state decays into a τ pair with a lifetime of the order of 20 ps.

PACS numbers: 13.85.-t, 14.65.Fy, 14.60.Fg, 14.80.-j, 12.60.Fr

The Higgs mechanism provides a scheme for the electroweak symmetry breaking (EWSB). Electroweak precision tests (EWPT) indicate that the standard model (SM) Higgs boson is light, $m_h < 186$ GeV/c^2 [1], with a central value considerably below the lower bound of 114 GeV/c^2 from direct searches [2]. While it is possible that one is misled in interpreting the EWPT data in terms of a light Higgs mass, the EWSB sector in the SM Lagrangian appears to be the most elusive and the one most likely to provide experimental surprises [3, 4, 5, 6]. In Refs. [7, 8], the CDF collaboration presents a set of studies of multi-muon events. Reference [7] uses multi-muon events to measure the correlated $b\bar{b}$ production cross section. That study is extended in Ref. [8] to additional properties of multi-muon events. Based on the properties of these events, this paper explores a possible conjecture of new physics that might relate the results of Ref. [8] to the EWSB mechanism.

The data set used in Refs. [7, 8] has been acquired with a dedicated dimuon trigger, and consists of events containing two central ($|\eta| < 0.7$) muons, each with transverse momentum $p_T \geq 3$ GeV/c, and with invariant mass larger than 5 GeV/c^2. References [7, 8] show that, when both trigger (initial) muons arise from particles that have decayed within the beam pipe of radius 1.5 cm, their number and kinematic properties are correctly predicted by a SM simulation. According to the simulation, approximately 96% of the known sources of dimuons, such as Drell-Yan, Υ, Z^0, and heavy flavor production, satisfy this condition. The sum of these contributions (1131090 events) is for simplicity referred to as QCD production [8]. Reference [8] also reports the observation of 295481 events, referred to as ghost events, in which at least one muon originates beyond the beam pipe. A large fraction of these events is attributed to muons arising from π, K, K^0_S, and hyperon decays as well as to secondary interactions in the detector volume. However, a small but significant fraction of these events has characteristics that cannot be explained by known processes in conjunction with the current understanding of the CDF II detector, trigger, and event reconstruction. Reference [8] has investigated the rate and kinematic properties of tracks and muons contained in a 36.8° cone around the direction of each trigger muon in ghost events. The nature of these events is characterized by four main features. The impact parameter [9] distribution of initial muon pairs is markedly different from that of QCD events. In 36.8° ($\cos\theta \geq 0.8$) cones around the initial muon direction, the rate of additional muons and charged tracks is significantly higher than that of QCD events. The invariant mass of the initial and additional muons distributes differently from that expected from sequential semileptonic decays of hadrons with heavy flavor. The distributions of the impact parameter of additional muons, and of the distance between the $p\bar{p}$ collision point and secondary vertices reconstructed using pairs of tracks contained in a cone, do not correspond to the lifetime of any known particle.

Although it is not excluded that the features of these events can be later explained in terms of known sources [8], this paper presents a phenomenological conjecture of new physics that shows that it is possible to account for the various features of these events, and also suggests additional observations that are further tested with the published data [8]. In this conjecture, a fraction of the ghost events is attributed to pair production of three new states h_1, h_2, and h_3 with masses in the range of 15, 7.3, and 3.6 GeV/c^2, respectively. The heavier states cascade-decay into the lighter ones, whereas the lightest state decays into a τ pair with a lifetime of the order of 20 ps [8].

Figure 1, reproduced from Ref. [8], shows the sign-coded multiplicity distribution of additional muons contained in a 36.8° cone around the direction of an initial muon in ghost events. In the plot, an additional muon increases the multiplicity by 1 when of opposite sign and by

10 when of the same charge of the initial muon. Leaving aside the case in which no additional muons are found, an increase of one unit in the muon multiplicity corresponds in average to a population decrease of approximately a factor of seven. This factor happens to coincide with the inverse of the $\tau \to \mu$ branching fraction (0.174) multiplied by the 83% efficiency of the muon detector, and suggests that these muons might arise from τ decays with a kinematic acceptance close to unity. We use Monte Carlo pseudoexperiments to model the shape of the muon multiplicity distribution in Fig. 1. The pseudoexperiments generate 4 τ^- + 4 τ^+ leptons and decay them into muons with a 17.4% probability. In the pseudoexperiments, initial and additional muons are identified with the measured [8] detector efficiencies of 50% and 83%, respectively. The pseudoexperiment result is shown in Fig. 1, in which the simulated distribution is normalized to the integral of the data for multiplicity bins higher than 10. The comparison of the muon multiplicity distribution in ghost events with the toy simulation suggests that approximately 13200 events contain 8 τ leptons inside a $\cos\theta \geq 0.8$ cone. One interpretation is that they are 8-τ decays of objects h_1 that are relatively light with respect to the transverse momentum with which they are produced.

Next, we test the data for an obvious consequence of the $h_1 \to 8\tau$ conjecture. If the hypothesis is correct, one expects that, when the h_1 transverse momentum is very large, the 8τ decays produce an average of 9.5 tracks with $p_T \geq 2$ GeV/c in a 36.8° cone. We compare the data presented in Ref. [8] to simulated events which contain h_1 states produced with large transverse momenta. We use the PYTHIA Monte Carlo program [10] to generate fictitious $p\bar{p} \to H \to h_1 h_1$ events followed by $h_1 \to 8\tau$ decays [11]. We use this process for convenience, without implying that the h_1 states might be Higgs bosons or might arise from Higgs decays. Figure 2 compares the average track multiplicity in the data and in some of the simulations. In order to reject the QCD contribution, Reference [8] considers events that contain at least three muons in a 36.8° cone. The figure shows the average number of tracks with $p_T \geq 2$ GeV/c contained in a 36.8° cone around a primary muon as a function of the total transverse momentum of the tracks. The asymptotic value of the average track multiplicity in the data adds support to the conjecture of a $h_1 \to 8\tau$ decay initially suggested by the muon multiplicity distribution.

In the assumption that leptons and tracks contained in a 36.8^0 cone around a primary muon arise from $h_1 \to 8\tau$ decays, the mass of the h_1 particle is determined by comparing data and simulations in the following invariants proportional to m_{h_1}: (a) the invariant mass of all muons in a cone when both cones contain at least two muons; (b) the invariant mass of all muons in a cone containing at least three muons; (c) the muon invariant mass for cones containing exactly three muons; (d) the invariant mass of muons and tracks for cones containing three or more muons and 5 to 6 tracks. Reference [8] shows that the request of a large number of muons suppresses the QCD contribution. In cases when fewer muons are requested, the QCD background is larger and has been subtracted in Ref. [8]. These invariant mass distributions are shown in Fig. 3. The data are compared to simulations of the process $H \to h_1 h_1$ with $m_H = 300$ GeV/c^2, and $m_{h_1} = 15$ and 20 GeV/c^2, respectively. A mass of 15 GeV/c^2, close to the invariant mass of 8 τ leptons, provides a fair modeling of the data, whereas a mass of 20 GeV/c^2 appears to be too high.

We investigate if the data are consistent with the hypothesis of h_1 pair production by studying the rate and properties of events in which two 36.8° cones contain a muon multiplicity larger than that of QCD events. In the sample of ghost events isolated by the study in Ref. [8], there are 27990 ± 761 cones containing two or more muons, 4133 ± 263 cones containing three or more muons, and 3016 ± 60 events in which both cones contain two or more muons. Figure 4 plots two-dimensional distributions of the invariant mass of all muons and of

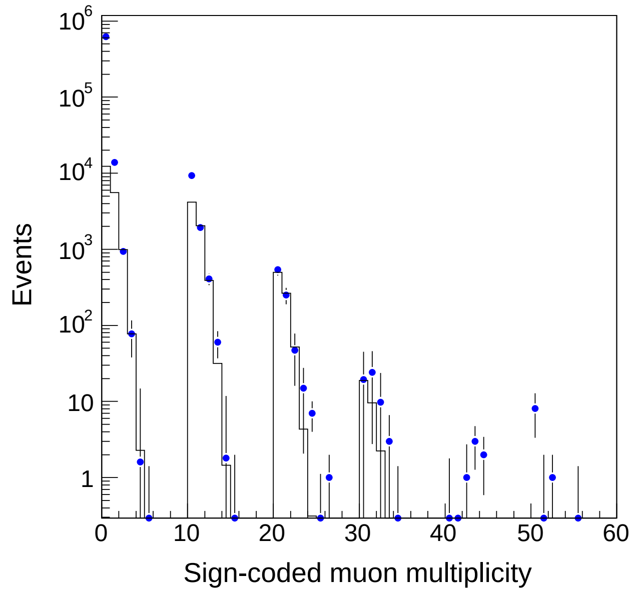

FIG. 1: Sign-coded multiplicity distribution of additional muons found in a $\cos\theta \geq 0.8$ cone around the direction of a primary muon in ghost events. The points are reproduced from Ref. [8], in which the QCD contribution has been removed and the distribution has been corrected for the fake muon contribution. An additional muon increases the multiplicity by 1 when it has opposite and by 10 when it has same sign charge as the initial muon. The first bin represents cones without additional muons. As examples, the third bin indicates cones with 3 muons with charge $(+ - -)$ or $(- + +)$; and the 21st bin indicates cones with 3 muons with charge $(+ + +)$ or $(- - -)$. The solid line is the prediction of the toy-simulation of a decay into eight τ leptons (see text).

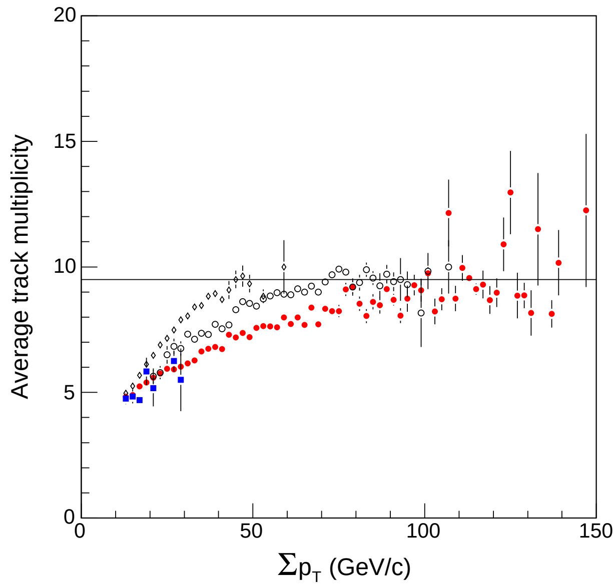

FIG. 2: Average number of tracks in a 36.8° cone around the direction of a primary muon as a function of $\sum p_T$, the transverse momentum of all tracks. Data ($\bullet$), reproduced from Ref. [8], are compared to a $H \rightarrow h_1 h_1$ simulation with $m_{h_1} = 15$, and ($\diamond$) $m_H = 115$ or ($\circ$) $m_H = 300$ GeV/c^2. The transverse momentum distribution of the data is different from that of the simulations, but the average number of tracks has the same asymptotic value, as indicated by the straight line. The QCD prediction ($\blacksquare$) is based on the few events predicted by the heavy flavor simulation, normalized to the number of initial muon pairs in the data and implemented with the probability that tracks mimic a muon signal.

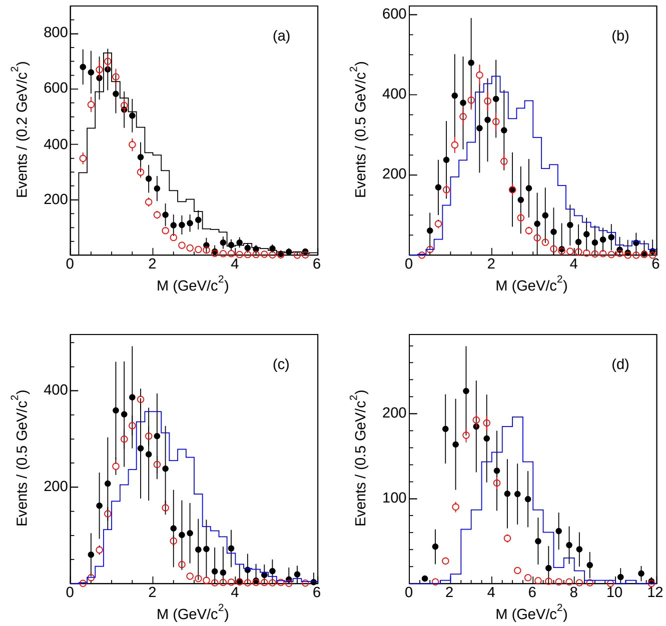

FIG. 3: Invariant mass, M, distributions of all muons in a 36.8° cone when (a) both cones contain at least two muons, (b) a cone contains three or more muons, (c) a cone contains three muons, and (d) of muons and tracks for cones containing 5 to 6 tracks and three or more muons. The fake muon contribution has been subtracted. The invariant mass distributions predicted by a simulation with $m_{h1} = 15$ ($\circ$) and $m_{h1} = 20$ GeV/c^2 (histogram) are superimposed to the data ($\bullet$) reproduced from Ref. [8].

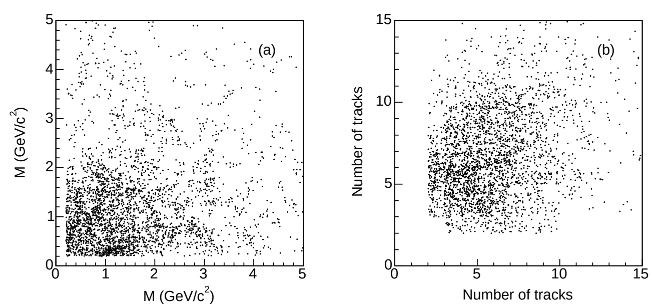

FIG. 4: Two-dimensional distributions, reproduced from Ref. [8], of (a) the invariant mass, M, of all muons and (b) the total number of tracks contained in a 36.8° cone when both cones contain at least two muons.

the number of tracks contained in each cone for the 3016 events. Figure 5 shows that the invariant mass distribution of all muons contained in the 27990 cones containing at least two muons is consistent with that of the 3016 events in which both cones contain at least two muons [8]. We compare the data to a simulation of the process $f\bar{f} \rightarrow h_1 h_1$ generated with the PYTHIA Monte Carlo program, in which the h_1 pair production is mediated by a photon exchange. In 8549600 generated events, we find 15580 events with a pair of initial muons that pass the analysis selection of Ref. [8]. These simulated events contain 7997 cones with two or more muons, and there are 1044 events in which both cones contain two or more muons. The ratio 1044/7997 is in quite good agreement with that of the data (3016/27990) [13]. Based on these comparisons, a fraction of the ghost events seems to be more consistent with the conjecture that h_1 states are pair produced.

The dependence of the h_1 pair production on the Mandelstam variable $\hat{s}$ is studied by comparing data to different simulations in the following distributions shown in Fig. 6: (a) the invariant mass of all muons for events in which both cones contain at least two muons; and (b) the invariant mass of all tracks for events in which both cones contain at least two muons. The data distributions do not show any evidence of resonant production. However, the data distributions fall less rapidly than in the $f\bar{f} \rightarrow h_1 h_1$ simulation, a possible indication that the h_1 pair production is not mediated by a photon or a gluon. The $f\bar{f} \rightarrow h_1 h_1$ distribution shown in Fig. 6 corresponds to a production cross section of 3.4 nb. Events in which the h_1 pairs have larger invariant mass are modeled with a simulation of the process $p\bar{p} \rightarrow H \rightarrow h_1 h_1$

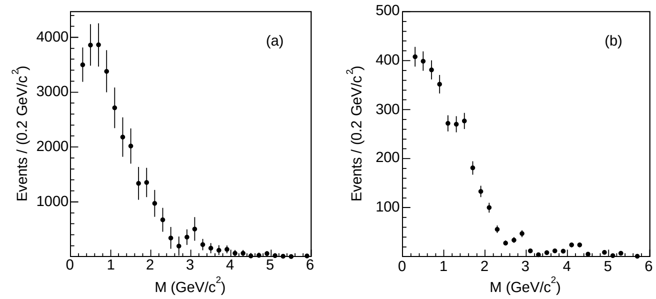

FIG. 5: Distributions, reproduced from Ref. [8], of the invariant mass, M, of all muons contained in (a) the 27990 36.8° cones with two or more muons and (b) the 3016 events in which both cones contain two or more muons. QCD and fake muon contributions have been removed.

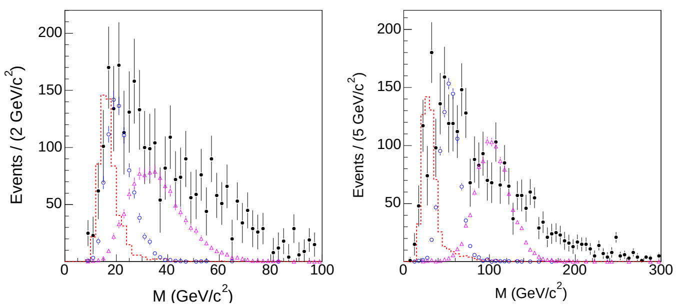

FIG. 6: Invariant mass, M, distribution of (left) all muons and (right) all tracks with $p_T \geq 2$ GeV/c for events in which both cones contain at least two muons. QCD and fake muon contributions have been removed. Simulations of the processes $f\bar{f} \rightarrow h_1 h_1$ (dashed histogram), and $H \rightarrow h_1 h_1$ with $m_H = 150$ ($\circ$) and 300 GeV/c^2 ($\triangle$) are superimposed to the data ($\bullet$) reproduced from Ref. [8].

with $m_H = 150$ and 300 GeV/c^2. The results of these simulations, also shown in Fig. 6, correspond to a production cross section of 50 and 35 pb for $m_H = 150$ and 300 GeV/c^2, respectively. Using the acceptances measured with these different simulations we again estimate that approximately 5% of the 295481 ghost events with two initial muons can be explained by pair production of h_1 particles.

In the assumption that ghost muons are produced in the decays of these states, the fits to the high impact parameter tail of additional muons in ghost events [8], where the distribution is well modeled by an exponential function, can be used to estimate their lifetime to be 21.4 ± 0.5 ps. If the h_1 states decay directly into 8 τ leptons with a lifetime of 20 ps, the impact parameters of muons due to ghost events would be highly correlated since the τ lifetime is negligible compared to that of the h_1 states. In contrast, the study in Ref. [8] finds a very weak correlation between the impact parameters of muons contained in the same cone. We compare data from Ref. [8] to simulations in order to test the more elegant conjecture of a three-stage decay $h_1 \rightarrow 2\, h_2 \rightarrow 4\, h_3$, where h_3 is the particle decaying into τ pairs. We use simulated samples of the processes $f\bar{f} \rightarrow h_1 h_1$ and $p\bar{p} \rightarrow H \rightarrow h_1 h_1$ with $m_H = 300$ GeV/c^2, in which the h_1 states decay into 8 τ leptons through a three-stage decay. We attribute in turn a 20 ps lifetime to only one of the h_1, h_2, and h_3 states. We measure the correlation between the impact parameters of muons contained in a 36.8° cone for the different cases. The correlation factor is $\rho_{d_p d_s} = 0.39$, 0.15, and 0.05 when the lifetime is attributed to the h_1, h_2, and h_3 states, respectively, whereas it is measured to be 0.03 in ghost events [8]. This indirect method provides evidence for the possible existence of two additional states, h_2 and h_3. The latter state is long-lived and decays into τ pairs. Following the assignment of a 15 GeV/c^2 mass to the h_1 state, one expects the h_2 mass to be in the range $7.1 - 7.5$ GeV/c^2 and the h_3 mass $\simeq 3.6$ GeV/c^2. The observed number and properties of the ghost events can accommodate the additional pair production of at least one of the h_2 and h_3 states. When the 20 ps lifetime is attributed to the h_3 state, only a few percent of the simulated events selected as in Ref. [8] survive the additional request that both initial muons originate inside the beam pipe. This models closely what happens in the data, as reported in Ref. [8].

Because the production mechanism of these hypothetical states is not understood, we cannot use the simulation to improve the measurement of the h_3 lifetime reported in Ref. [8]. However, we highlight one difficulty that arises if ghost events are due to mixed pair production of h_1, h_2, and h_3 states. In Ref. [8], the lifetime of the muon parent particle has been estimated by fitting with an exponential function the muon impact parameter distributions in the range $0.5 - 2.0$ cm. We have produced simulated samples of h_n pair production using the processes $f\bar{f} \rightarrow h_n h_n$ and $p\bar{p} \rightarrow H \rightarrow h_n h_n$ with $m_H = 300$ GeV/c^2 and $n = 1, 2, 3$. In these simulations, states heavier than the h_3 particles cascade-decay into them and ultimately produce events with 4, 8, and 16 τ leptons in the final state. We generated several samples with h_3 lifetimes ranging from 10 to 40 ps. For simulated events due to h_3 or h_2 pair production, analogous fits to the impact parameter distributions return the lifetime value used in the event generation. However, in the simulation of h_1 pair production, some of the h_1 cascade-decay products are not relativistic and the decay kinematics has greater complexity. As a consequence, the fits to the impact parameter distributions underestimate the lifetime by approximately 30%.

The identification of τ decays into three hadrons would provide additional support to the conjecture of new physics used to account for a fraction of the ghost events. This decay channel could also be used for a complementary measurement of the h_3 lifetime by using the L_{xy} distribution of the three-track secondary vertices, where L_{xy} is the distance between the secondary vertex and the $p\bar{p}$ collision point projected onto the transverse momentum

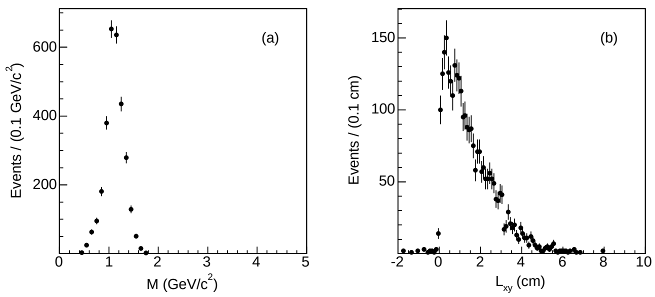

FIG. 7: Distributions of the (a) invariant mass and (b) distance L_{xy} (see text) of three-track systems in events simulated with the process $p\bar{p} \rightarrow H \rightarrow h_1 h_1$ with $m_H = 150$ GeV/c^2. The three-track systems are produced by single τ decays into three hadrons.

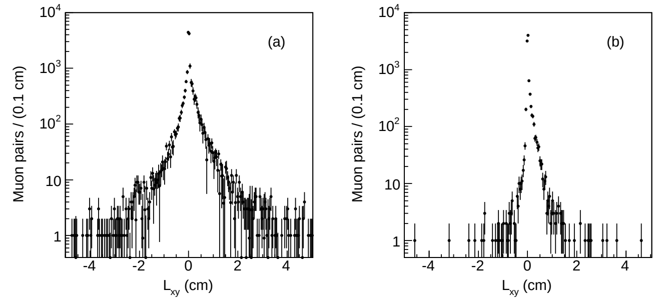

FIG. 8: Distribution, reproduced from Ref. [8], of the distance L_{xy} of fit-constrained vertices of three-track systems contained in a 36.8° cone around the direction of an initial muon for (a) ghost and (b) QCD events. We select cases in which angular cones contain only three tracks.

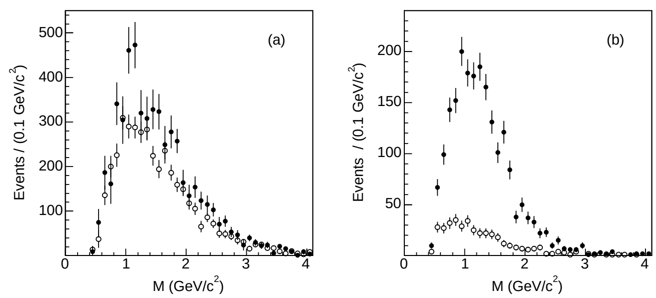

FIG. 9: Distributions, reproduced from Ref. [8], of the invariant mass, M, of three-track systems in (a) ghost and (b) QCD events. Systems with distance $L_{xy} \geq 0.04$ cm ($\bullet$) are compared to those with $L_{xy} \leq -0.04$ cm ($\circ$). Ghost events with positive L_{xy} exhibit an excess of events with the expected shape of τ into three hadron decays.

of the three-track system. Reference [8] has searched the data for such secondary vertices, and has verified the detector response by using identified $K^0_S \rightarrow \pi^+\pi^-$ decays. That study [8] reconstructs three-prong secondary vertices by using tracks with $p_T \geq 1.0$ GeV/c and $|\eta| \leq 1.1$ in a 36.8° cone around the direction of each initial muon. Track systems with total charge of ± 1 are constrained to arise from a common space point. In this study, we use similar criteria to search for hadronic τ decays in simulated events, and compare our result to the published data [8]. In a sample generated with the process $p\bar{p} \rightarrow H \rightarrow h_1 h_1$ with $m_H = 150$ GeV/c^2, there are in average two τ decays into three hadrons per event. Approximately 8% of these decays, or 0.16 τ hadronic decays per event, survive these selection criteria. Figure 7 shows the invariant mass and L_{xy} distributions of the three-track systems that are also identified at generator level as τ decays into three hadrons.

The simulation also contains 5.5 three-track combinations per event that pass the same selection criteria, and the signal of the 3-hadron τ decays is swamped by the combinatorial background. However, this signal is comparable to the combinatorial background in a simulated sample of h_3 pair production in which a 36.8° cone contains sometimes one muon and three tracks from the two τ decays. In this case, the vertices of the three-track systems identify correctly the h_3 decay vertex and generate an excess of events at positive L_{xy} distances. Reference [8] presents a subsample of ghost events in which a 36.8° cone around the direction of an initial muon contains only three tracks with $p_T \geq 1$ GeV/c. Three-track systems with total charge of ± 1 are constrained to arise from a common space point. Figure 8 shows the L_{xy} distribution for ghost and QCD events [8]. Ghost events show an excess at positive L_{xy} that is, however, not as large as that of QCD events in which most of the muon plus the three-track combinations arise from single b-quark decays. Figure 9 compares the invariant mass of the three-track systems for positive and negative L_{xy} values [8]. In the case of ghost events, the invariant mass of three-track systems with positive L_{xy} exhibits an excess of events consistent with the shape of τ decays into three hadrons shown in Fig. 7.

In conclusion, we suggest one possible phenomenological interpretation of the multi-muon events recently reported by the CDF collaboration. As shown by the comparisons between the published data and simulations based on our conjecture, the most interesting features of these events can be accounted for by postulating the pair production of three new states h_1, h_2, and h_3 with masses in the range of 15, 7.3, and 3.6 GeV/c^2, respectively. The heavier states cascade-decay into the lighter ones, whereas the lightest state decays into a τ pair with a lifetime of the order of 20 ps. The mechanism that produces h_1 pairs is completely obscure. It does not appear to be resonant nor mediated by a photon or gluon exchange. The observed pair production cross section ($\simeq 100$ nb) is a few orders of magnitude larger than what is predicted if the h_n states belonged to the Higgs sector [3, 6].

We thank the Fermilab staff and the CDF collaboration institutions for their contributions. This work was supported by the U.S. Department of Energy and

National Science Foundation and the Italian Istituto Nazionale di Fisica Nucleare. We are indebted to S. Mrenna for guiding us through several subtleties of the PYTHIA Monte Carlo program.

---

[1] The ALEPH, DELPHI, L3, and OPAL Collaborations and the LEP Electroweak Working Group, *A Combination of preliminary electroweak measurements and constraints on the standard model*, arXiv:hep-ex/0612034.

[2] The ALEPH, DELPHI, L3, and OPAL Collaborations, Phys. Lett. B **565**, 61 (2003).

[3] R. Dermisek and J. F. Gunion, Phys. Rev. D **76**, 095006 (2007).

[4] E. Fullana *et al.*, Phys. Lett. B **563**, 67 (2007).

[5] S. Chang *et al.*, arXiv:0801.455v2.

[6] M. J. Stressler *et al.*, Phys. Lett. B **651**, 374 (2007).

[7] T. Aaltonen *et al.,* Phys. Rev. D **77**, 072004 (2008).

[8] T. Aaltonen *et al.,* arXiv:0810.5357.

[9] The impact parameter is the distance of closest approach of a track to the primary event vertex in the plane transverse to the beam direction.

[10] T. Sjöstrand and M. Bengtsson, Comp. Phys. Commun. **43**, 367 (1987); H. Bengtsson and T. Sjöstrand, Comp. Phys. Commun. **46**, 43 (1987); T. Sjöstrand *et al.,* Comp. Phys. Commun. **135**, 238 (2001).

[11] We have generated several simulated samples with a Higgs mass, m_H, ranging from 115 to 300 GeV/c^2 using the option ISUB=151 of the version 6.4 of the PYTHIA Monte Carlo program. We have also generated pair production of Higgs bosons ($f\bar{f} \to h_n h_n$) with the option ISUB=300. The h_n widths are set to be negligible with respect to the detector resolution. We use the interface PYSLHA.F and decay Higgs bosons according to phase space. The τ decays are simulated with the TAUOLA program [12]

[12] S. Jadach *et al.,* Comp. Phys. Commun. **76**, 361 (1993). We use TAUOLA Library version 2.6.

[13] In a different simulation, that uses the process $p\bar{p} \to H \to h_1 h_1$ with $m_H = 300$ GeV/c^2, this ratio is a factor of two higher than in the data because heavy resonant states are decayed by the PYTHIA generator program into h_1 pairs with well balanced transverse momenta.